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How will climate change impact biomass increment by Norway spruce stands in Western Beskids?

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Abstract

The objective of this study is to analyse the relationship between current climatic conditions and the growth of Norway spruce, and to simulate the effect of changes in temperature and precipitation resulting from increased carbon dioxide concentration on the potential site productivity and carbon sequestration by Norway spruce in the Western Beskids, southern Poland. The research material was data from 43 meteorological stations and posts, and data from 387 permanent sample plots from the Norway spruce stands. On the basis of historical climate data using the WGENK model (Kuchar 2005) a series of meteorological data was generated with a time horizon of 100 years. The calculation procedure was based on two scenarios – CO_2 concentrations of 130% and 200% by 2050. In the case of scenario assuming the doubling of CO_2 concentration in the atmosphere, the growth in mean annual temperature projected under this scenario of about 2.7ºC and the reduction in the rainfall during the growing season by about 70 mm would result in a significant deterioration in conditions for spruce growth up to 1000 m asl. A slightly better prospect for the growth of spruce in the Western Beskids would take place in the GISS_E_WC scenario (Durło 2011), which assumes a 30% increase in CO_2 concentrations. As a result of the increase in mean annual air temperature by about 0.7ºC while maintaining the current level of mean annual precipitation and a slight reduction in rainfall during the growing season, a slight deterioration in habitat conditions to a height of about 800 m asl, optimal growth conditions for spruce would occur in the zone between 850 and 1000 m asl. These analyses of spruce site conditions in the Western Beskids may be the basis for decisions concerning the future role of this species in the species composition of stands, depending on their location.

Key words

climate scenario, biomass increment, potential productivity, site index

Introduction

In recent decades, changes in certain climatic indicators have been observed in Central Europe, and subsequent implications are expected in the future (IPCC 2007, EEA 2008, Albert and Schmidt 2010). Owing to the complex interactions between climatic factors, it is difficult to predict changes in the climate in detail, but

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making some assumptions it is possible to simulate general trends. It is assumed that human activities increase atmospheric carbon dioxide concentration by 1.0% each year. With doubling CO_2 concentration within the next 100 years it is expected to raise the average air temperature by about 3.0°C (IPCC 2007). Climate change impacts on growing conditions and results in general in accelerated growth and rising net primary production of some tree species in several parts of Europe. Environmental changes also affect the vitality and stability of forest stands (Pretzsch 1985; Spiecker et al. 1996; Hasenauer et al. 1999; Rötzer et al. 2005; Mellert et al. 2008; Durło 2011).

The following climate change trends projected for Central Europe will also have a heavy impact on forest ecosystems: an increase in temperature, with warmer summers and considerably warmer winters that extend growing seasons; a shift in precipitation with less rainfall in summer and increased precipitation in winter; increasing CO_2 and NO_x in the atmosphere; and more frequent weather extremes such as droughts, extreme precipitation and wind events (Beerling 1999; Constable and Friend 2000; Lindner 2000; Matala 2005; Andreassen et al. 2006; Ekö et al. 2008; Skovsgaard and Vanclay 2008; Albert and Schmidt 2010).

In mountain environments, climate is one of the main factors limiting the growth of forest trees (Frits 1976; Saava et al. 2006; Socha 2008). Therefore, the changes in certain climatic parameters observed over recent decades in mountain areas are of particular importance (Migała 2005; Durło 2010a, 2010b). The effect of climatic factors on tree and forest stand growth varies with altitudinal gradient from low-elevation to high elevation sites (Saava et. al. 2006). In high elevation sites, the most important growth-limiting factor is air temperature, whereas at low-elevation sites tree and forest growth is influenced much more by precipitation (Mäkinen et al. 2002).

Forests are very important for sustainable development in mountain areas. In Central Europe, in addition to wood production, mountain forests are essential for water retention, erosion protection and tourism development. The extremely long production period for forestry means that there is a need for simulations and projections of the possible effects of climate change on growth of forest stands for the purposes of strategic forest management planning aimed at reducing the risk of disturbing the stability of the forest ecosystem. Such simulations constitute decision support for forest managers to assist them in meeting the challenges of climate change (Albert and Schmidt 2010). The most important forest-forming tree species in mountainous areas of Central Europe is Norway spruce. There are several studies showing contrasting results for the climate-growth relationship of Norway spruce depending on altitude and latitude (Mäkinen et al. 2002; Modrzyński and Eriksson 2002; Andreassen et al. 2006; Saava et al. 2006). In general, it is expected that projected climate change will increase the potential site productivity for Norway spruce. Increase in the site productivity for Norway spruce is expected, *inter alia*, in Sweden and Slovakia, in Canada, and also in Germany (Fries et al. 2000; Ďurský et al. 2006; Albert and Schmidt 2009). The disintegration of Central European mountain spruce stands observed in recent years seems to contradict the assumed increasing site productivity for this species. Given the high economic importance of spruce, in this era of observed climate change there is an urgent need to attempt to answer questions about the possibility of spruce growth in the mountains of Central Europe, and the advisability of using spruce as the main forest forming species in forest regeneration. In order to answer this question, this study presents an analysis of the impact of current and projected weather conditions on the growth of forest stands in the mountains.

Material and methods

The investigations were carried out in the Western Beskids (18°48'50" E and 19°58'58" E longitude and 49°23'52" N and 49°41'3" N latitude) in the Western Carpathians region, southern Poland. They are the second highest mountain range in Poland, located in the main watershed of the drainage areas of the Baltic Sea and Black Sea (Fig. 1).

The highest peaks of the Silesian Beskids are Skrzyczne (1257 m) and Barania Góra (1220 m). The highest peaks of the Żywiec Beskids are Babia Góra (1725 m) and Pilsko (1557 m). The average decrease in the area is 15°, and slopes of 5° to 20° dominate. The area of the Western Beskids is about 1053 km², of which 62% of the area covered is by forest stands. Most of the for-

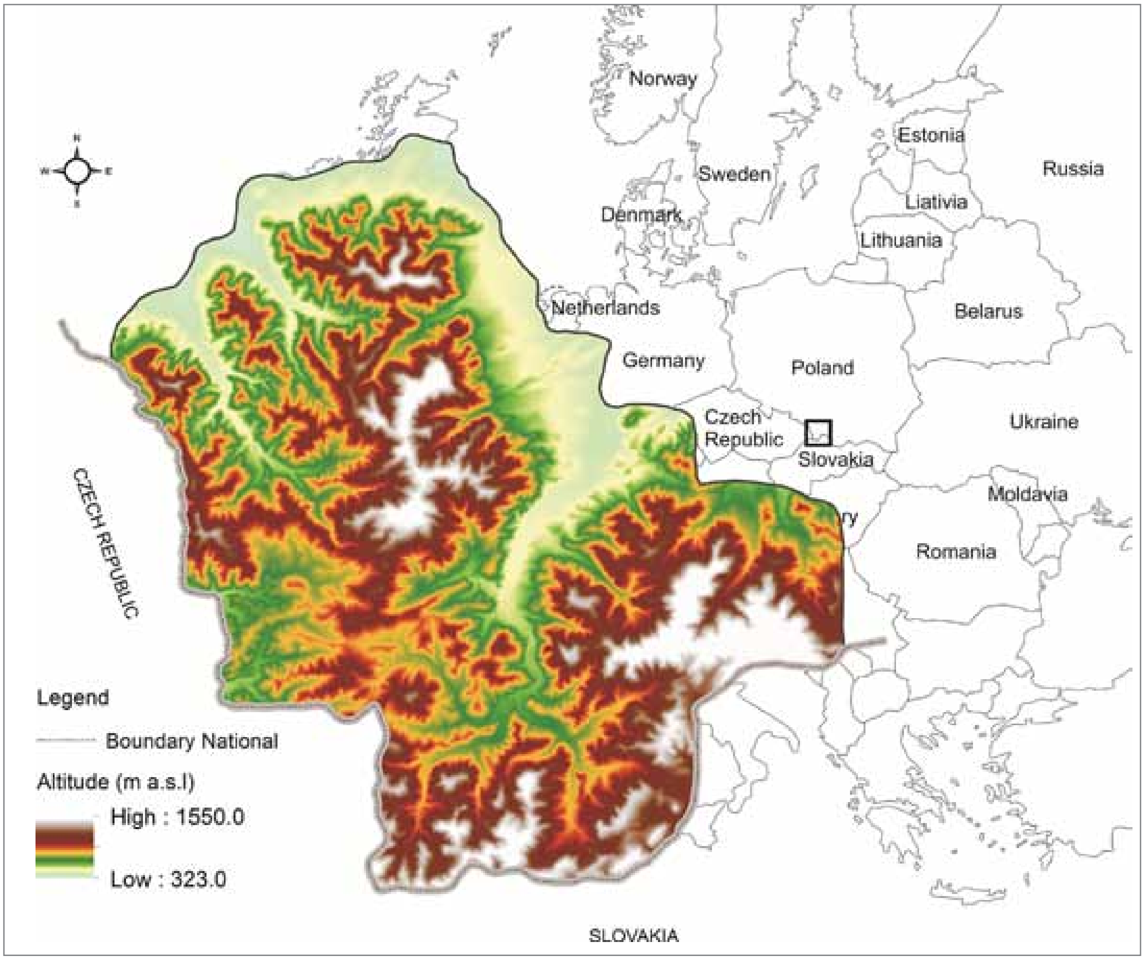

Fig. 1. Geographical position of the study area in southern part of Poland

est area is occupied by spruce stands (74%). They occur in the lower and upper subalpine zones, at heights ranging from about 400 to 1400 m asl (Wilczek 1995). The remaining areas are covered by natural forests of mixed beech, riparian ash, mountain sycamore, lower subalpine fir and spruce, and at higher altitudes poor acidophilous beech (Barański 2007).

Climate

The area of the Western Beskids belongs to the Carpathian climate zone situated in a temperate climate area. The polar-sea air masses, with dominant westerly winds, have the greatest influence on the weather. According to Romer's classification (1962), the area under discussion belongs to the mountain climatic region, F7 Silesian and Western Beskids. Average annual temperature in the survey area is 5.8°C with a deviation of 0.7°. The highest average is represented by outposts in Bielsko-Biała and Nowy Dwór, where it ranges from 7.7° to 7.9°C with a standard deviation of 0.8°. The annual average in this altitude zone increases slightly towards the west, reaching a value of 8.1°C in Cieszyn. The lowest annual average is at the summit of Pilsko and is 1.9°C with a deviation of 0.8°. The average annual rainfall is 1260 mm of water per m^2 with a deviation of 160 mm. The most abundant rainfall is in July, while the least precipitation falls in February and March. The highest rainfall zone covers the peak areas of the Wiślański Range and the Pilsko Massif. The average ratio of total precipitation from winter to summer is 71% (Hess 1965; Okołowicz 1969; Hess et al. 1984; Feliksik and Durło 2004; Durło 2011).

The basic material for the climate characteristics of the Western Beskid includes meteorological data from the period 1956–2008 obtained from the IMGW in Warsaw (Institute of Meteorology and Water Management) and the Katowice GCHM archives (Hydro-Meteorolocial Centrum). The study used the following materials: climatological journals, record book of precipitation, monthly lists of meteorological observations, pluviograms and collections of electronic REG CM3 database from years 1948–2008 for Central Europe, GCOS data (*Global Climate Observing System*), ICTP (*International Centre for Theoretical Physics*), and DC NOAA data with yearly climate indexes from 1948–2008. Homogeneity analysis of data series was performed in accordance with the applicable methods of Peterson and Easterling (1994), Próchnicki (1987) and Tuomenvirta (2001).

43 meteorological stations currently operate in the study area, most of which using a semi-automatic or automatic measuring program. The outposts are located across the physical-geographical unit over the full altitude range. Twenty four are situated within concave terrain forms, the remainder on convex. The analytical and cartographical studies were conducted for the air temperature and sum of precipitation. The theoretical basis for the geostatistical analysis is taken from the work of McBratney and Webster (1981), Spruill and Candela (1990), Van Groenigen and Stein (1998), Warrick and Myers (1987), Winkel and Stein (1997) and also Durło (2006). The statistical analysis of the results was performed using STATISTICA 9.0 (Data Analysis Software System, Version 9.0, StatSoft, Inc. 2009).

Data from Norway spruce stands were collected in 2003–2008 from 334 sample plots located in even-aged spruce stands aged 40–157 years (Tab. 1). The studied stands are located between 500 and 1360 m a.s.l. Of the sample plots, 64 are fixed rectangles of 0.5 ha area (58 stands) or 0.25 ha (six stands). These plots are randomly located across the whole study area. The remaining 270 plots are circular and their size varies from 0.02 to 0.10 ha. They are located in a regular (1250 × 1250 m) grid of research plots. Both large, fixed rectangle and circular sample plots cover the whole study area. Diameters at breast height and tree heights were measured in the sample plots. For large plots, the height of every fourth tree was measured, while for the circular plots all heights were measured. The age of stands was determined for at least six dominant trees by counting the number of rings in increment cores extracted using an increment borer at a height of about 20–25 cm above the ground surface, and adding the 3 years required to reach this point of extraction. In general, the difference in age among individual trees on the sample plots was no more than 3–5 years. The top heights for individual sample plots vary from 14.46 to 45.78 m and were estimated as the mean height of the 100 thickest trees

Tab. 1. Characteristics of sample plots

Type of characteristics	Variable	Statistical characteristics			
		Mean	Min	Max	Standard deviation
Biometrical characteristics	Age (years)	87	40	157	23,5
	Mean diameter (cm)	34,2	16,4	63,6	7,71
	Mean height (m)	28,3	12,8	44,8	5,99
	Top height (m)	30,6	14,5	45,8	5,59
	Site index (m)	33,0	11,8	44,1	5,02
	Breast height basal area ($m^2 ha^{-1}$)	43,5	17,6	75,6	10,53
	Stand volume ($m^3 ha^{-1}$)	572	144	1212	182
	Current annual volume increment ($m^3 ha^{-1} year^{-1}$)	15,3	1,4	35,8	6,05
	Number of trees per ha	531	80	2600	315
	Stand density index (SDI)	498	32	5130	516
Characteristics of location	Elevation a.s.l. (m)	884	530	1360	168
	Slope (°)	16,3	2,0	38,0	6,71

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per hectare. In the case of individual sample plots, the number of trees corresponding proportionally to the plot area was used, e.g. the 10 largest trees in 0.10 ha plots or the five largest trees in 0.05 ha plots. The mean heights of the thickest trees were calculated as the regression mean from height curves drawn up for particular sample plots.

The age (T_1) and mean height (H_1) of the stand were used to determine the site index (SI) for individual sample plots. For each plot, the site index at reference age (T_{SI}) 100 years was calculated from the local site index model developed for Norway spruce in the Western Beskids (Socha 2011, equation 1).

$$H_2 = H_1 \frac{T_2^{1,95817}(T_1^{1,95817}R + 66568,71)}{T_1^{1,95817}(T_2^{1,95817}R + 66568,71)} \tag{1}$$

where

R – denotes expression described by equation 1.1

$$R = -15,03036 + H_1 + \\ + \sqrt{\left(-15,03036 + H_1\right)^2 + \frac{2 \cdot H_1 \cdot 66568,71}{T_1^{1,95817}}} \tag{1.1}$$

To calculate the site productivity expressed by the increment of total biomass productivity, a mathematical equation was developed describing the relationship between the total biomass productivity of stands and age and site idex. For this purpose, spruce stand yield and growth reference data was used from yield tables (Schwappach 1943) which contain the total productivity of fully stocking stands of different site classes. Total volume productivity was conversed to total biomass productivity using biomass expansion factor (BEF) for Norway spruce (equation2, Lehtonen et al. 2004)

$$BEF = 0.501 + 0.193 \cdot e^{-0,01 \cdot A} \tag{2}$$

The dependence of total biomass productivity on site index was described by an empirical equation in which the total biomass production of spruce stands is a function of age, and site index (equation 3)

$$PTP = \left(\psi_4 \cdot SI - \psi_5\right) \times \left(\frac{1 - e^{\psi_1 \cdot T_1}}{1 - e^{\psi_1 \cdot T_{SI}}}\right)^{\psi_2 \cdot (\psi_4 \cdot SI - \psi_5)^{\psi_3}} \tag{3}$$

where:

PTP – potential total biomass productivity of the stand in age T_2,

T_1 – age of the stand,

SI – site index expressed as the mean height in base age T_{SI},

$\psi_1, \dots, \psi_5$ – the equation parameters.

Using this model, the potential mean total biomass productivity to the age of 100 years was calculated. The analysis also used the digital terrain model (DTM) for the Silesian and Żywiec Beskids at a scale of 1 : 10,000 with a grid size of 10 × 10 m. The high resolution DTM was built using data from aerial photos taken by the CODGiK in Warsaw (Head Office of Geodesy and Cartography). Based on data from meteorological stations for each pixel of the model grid, the mean annual temperature (*MAT*) and mean annual precipitation (*MAP*) were calculated, as well as the value of these same indices in two different climate scenarios. During the calculation procedure, two variant projected CO_2 concentrations were proposed: in the first case a doubling the concentration of carbon dioxide by 2050 (GISS_E) was assumed, while the second option assumed an increase in gas concentration of 130% during the same period GISS_E_WC (Durło 2010a, 2011). The base year for projections of CO_2 concentration was 1988 (EU COM Resolution 2008/17). The series of projected meteorological elements was generated by the WGENK generator (Richardson and Wright 1984; Richardson 1985; Kuchar 2005).

In order to determine the climatic characteristics for sample plots located in spruce stands, the coordinates were established in the 1964 system and then *MAT* and *MAP* values were determined for them. The next step was to develop climate models for potential productivity that described the relationship between potential site productivity, expressed as the annual total productivity increment at age 100 years, and climate indicators.

In order to describe the relationship between the potential mean annual biomass increment at with climate indices, a unimodal dose-effect-curve was used (equation 7). The value of $I_{b\max}$ (maximal biomass increment rate) was empirically estimated on the base of data collected as 9.909 Mg·ha^{-1}. On the base of mountain forest limit, the $MAT_{\min}$ value of temperature for Norway spruce was estimated at 1.9°C, whereas the $MAP_{\max}$ value for precipitation was approximated empirically on the base of an accuracy of dose-effect curve fitting at 1800 mm. Values of $MAT_{\max}$ for air temperature and $MAP_{\min}$ for precipitation were assumed at 11.0°C and 500 mm respectively, on the basis of a comparison of

climatic map for Poland and the limit of distribution of Norway spruce in Poland. According to Pretsch's (2009) proposition, to model the effect of precipitation and temperature, the dose-effect-functions for these factors were multiplied (equation 4)

$$I_b = I_{b\max} \times \Big(1 - e^{-c_p \times \left(MAP - MAP_{\min}\right)} + -e^{-c_d \times \left(MAP_{\max} - MAP\right)}\Big) \times \times \Big(1 - e^{-c_p \times \left(MAT - MAT_{\min}\right)} + -e^{-c_d \times \left(MAT_{\max} - MAT\right)}\Big) \quad (4)$$

where:

I_b – denotes biomass increment rate,

MAP, *MAT* – are respecively the mean annual precipitation and temperature estimated for individual sample plots.

The parameters for the abovementioned models were estimated using the nonlinear regression estimation method. The climatic models of potential productivity developed were used for forecasting the effect of climate change on the potential biomass increment of Norway spruce stands. The projected change in site productivity was elaborated for two climate change scenarios.

Results

Based on the data contained in the growth and yield tables (Schwappach 1943) converted with the use of *BEF* (equation 2), a mathematical model was developed describing the relationship between the total biomass productivity of the stand, its age and site index. Because the tabular values are given for fully stocked stands, the model total biomass productivity values for the stands at a given age in specific site conditions are the potential values. The equation developed (equation 5) faithfully reproduces the relationship included in the tables, since the coefficient of determination indicating the quality of the model fitting is 99.91%

$$TBP = \left(33.2009 \cdot SI + 352.5033\right) \times \times \left(\frac{1 - e^{-0.0299 \times T_1}}{1 - e^{-0.0299 \times T_{SI}}}\right)^{120.5875 \times (33.2009 \cdot SI + 352.5033)^{-0.4944}} \quad (5)$$

Based on the model obtained, using the age and site index estimated for individual sample plots, the increment in total aboveground biomass productivity was calculated (Fig. 2). Then, in order to describe the relationship between the biomass productivity increment and the climate conditions, *MAT* and *MAP* values were determined for individual sample plots.

Climatic data from 43 stations was used to prepare the multiple regression models. The *MAT* is described by equation 6, which, based on the variables elevation asl and latitude (X), explains approximately 95.0% of the variation in this indicator, the standard error of estimate (SEE) is 0.22°C.

Equation 7 describes *MAP*. The *MAP* value is correlated with the elevation asl and can be described as a function of one variable, which explains about 76% of the variation, while the SEE equals 68 mm.

$$MAT = 1.4966 \times X - 0.0046 \times E - 65.2151 \quad (6)$$

$$MAP = 850.74 + 0.4582 \times E \quad (7)$$

To describe the dependency of the volume increment at age 100 years on the *MAP* and *MAT*, the product of the two unimodal dose effect functions (equation 4) was used. Based on the analysis, it was concluded that climatic factors strongly correlate with the potential annual increment in the year at age 100 (R = 0.82, p < 0.0001) and explain approximately 67% of the variability of this variable. This relationship is described by equation 8 (Fig. 3)

$$I_b = 9.909 \times \Big(1 - e^{-0.2800 \times (MAPS - 500)} + -e^{-0.00564 \times (1550 - MAPS)}\Big) \times \times \Big(1 - e^{-0.72654 \times (SRTP - 1.9)} + -e^{-2,85323 \times (11 - MAT)}\Big) \quad (8)$$

Using a DTM and a model describing the relationship between *MAT*, *MAP* and annual biomass increment and the equations describing the spatial distribution of climate indexes (equations 6 and 7), a map was drawn up of the current potential biomass productivity for spruce in the study area (Fig. 4).

In the next stage of research on the *MAT* and *MAP* values forecast for individual meteorological stations according to the two scenarios adopted, regression models were drawn up describing the spatial distribu-

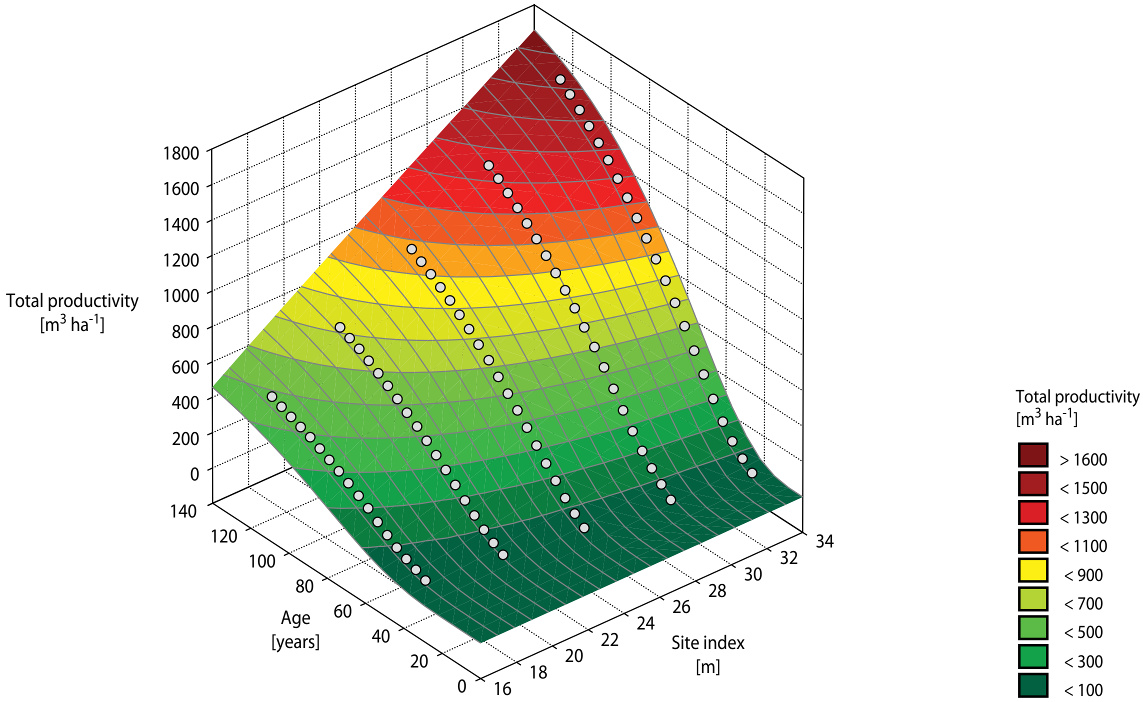

Fig. 2. Potential total biomass productivity of Norway spruce as a function of site index and age of the stand

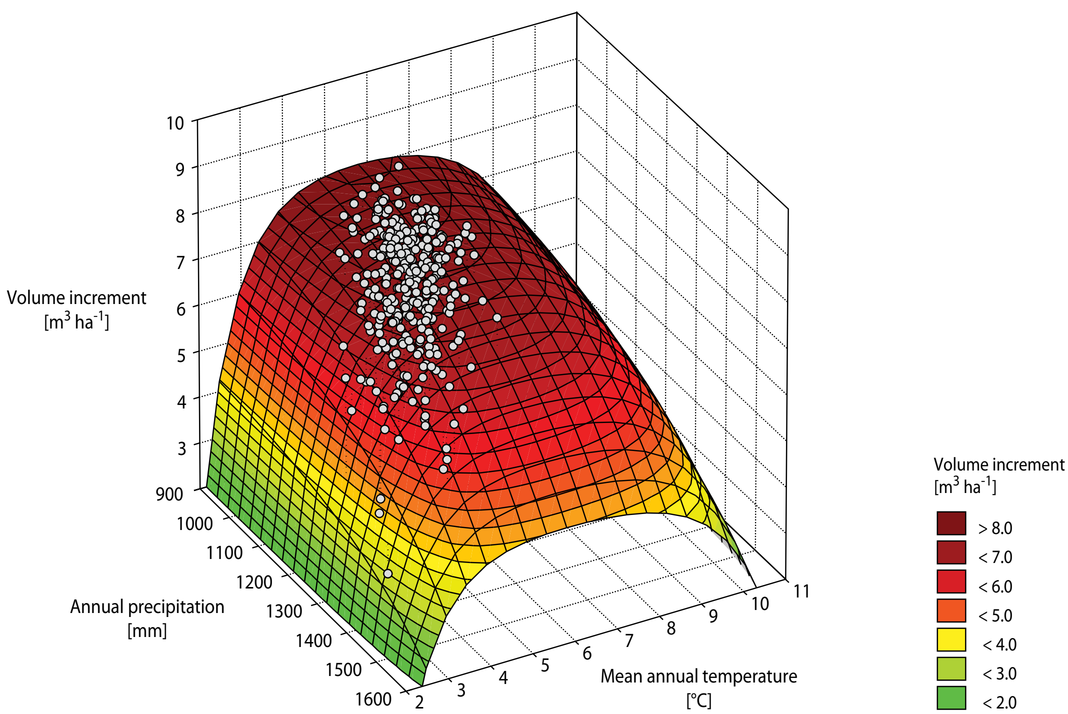

Fig. 3. Response of current annual volume increment in age 100 years to mean annual temperature (*MAT*) and mean annual precipitation (*MAP*) described by product of two two-dimensional, unimodal dose-effect functions (equation 8), where MAT_{min} = 1.9°C, MAT_{max} = 11°C, I_{bmax} = 9.909 Mg·ha^{-1}, MAP_{min} = 500 mm, MAP_{max} = 1800 mm

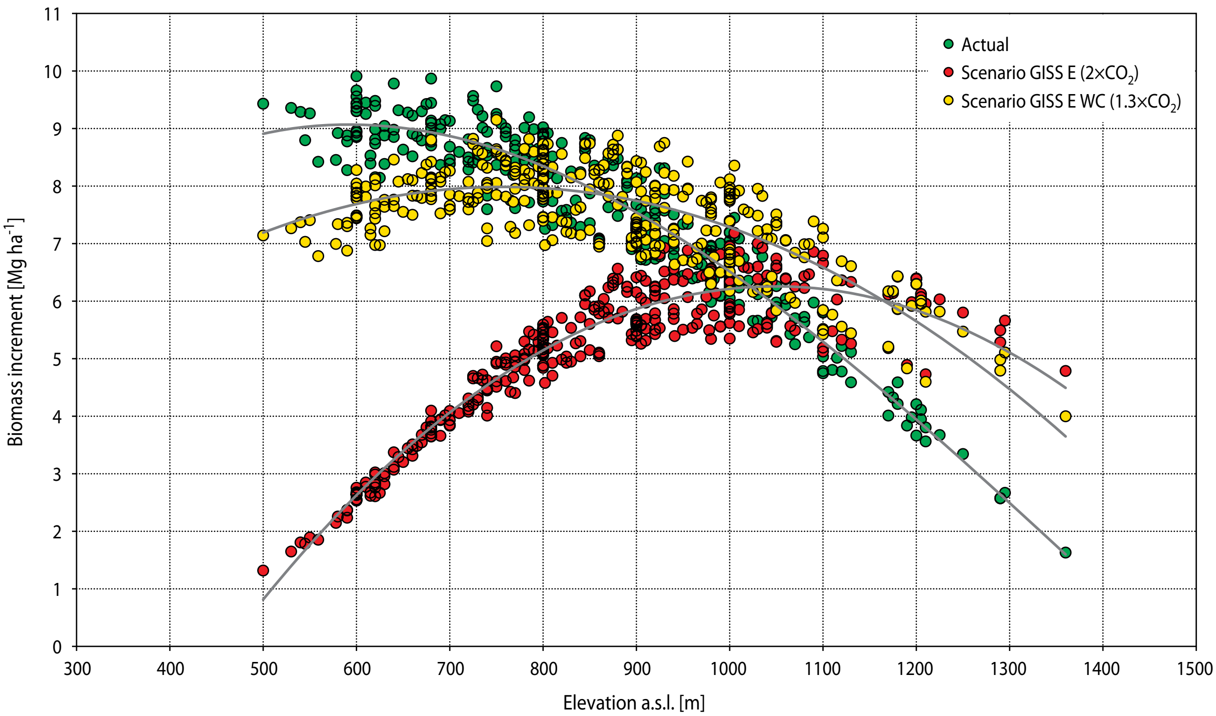

Fig. 4. Potential annual biomass increment in Norway spruce stads – actual and forecasted for two emissions scenario: GISS_E and GISS_E_WC

tion of *MAT* and *MAP* for scenario GISS_E (equations 9 and 10) and scenario GISS_E_WC (equations 11 and 12)

$$MAT_{2CO_2} = -0.00509 \times E + 12.812 \tag{9}$$

$$MAP_{2CO_2} = 402.9 \times X + 0.50 \times E - 19158.1 \tag{10}$$

$$MAT_{1.3CO_2} = -0.00494 \times E + 10.755 \tag{11}$$

$$MAP_{1.3CO_2} = 410.3 \times X + 0.50 \times E - 19524.4 \tag{12}$$

Based on the equations developed for each DTM pixel, including the pixels within which the test areas were located, projected values for *MAT* and *MAP* were calculated following the scenarios for the year 2100. In turn, substituting the predicted climatic index values in model 8 for individual sample plots, two values for each were obtained for the potential annual biomass increment (scenarios 1 and 2).

Then, the relationship between the current and projected values of potential biomass increment for spruce and the altitude asl was analysed. This relationship led to the conclusion that the climate change scenario 1 would significantly deteriorate the site conditions for spruce in the lowest locations (Fig. 5).

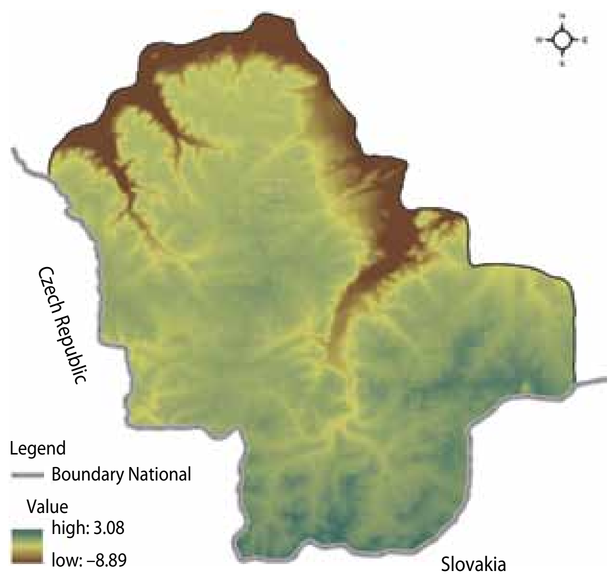

Fig. 5. Map of projected changes in the annual biomass increment under the assumptions of a twofold increase in the concentration of CO_2 (Scenario I - GISS E)

Under these conditions, the potential annual biomass increment of spruce stands would decrease by

about 8 Mg ha-1 in the lowest locations to about 3 Mg ha-1 at an altitude of about 800 m asl. Only above about 1000 m asl conditions for spruce growth and resulting biomass increment would be improved (Fig. 4). For the second climate scenario (GISS_E_WC), a temperature rise of about 0.7°C and a reduction in total precipitation during the year by about 7–9% would cause a small reduction in current annual increment in the lower montane zone.

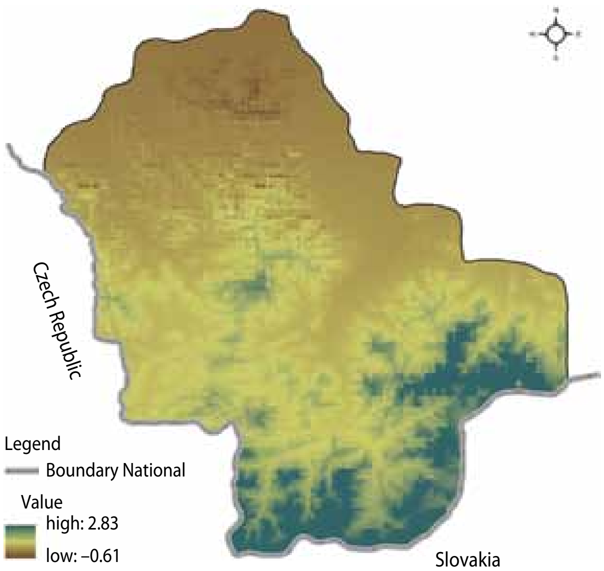

Fig. 6. Map of projected changes in the annual biomass increment under the assumptions of a 30% increase in the concentration of CO_2 (Scenario II – GISS E WC)

In the lowest locations, this decline would be about 2 Mg·ha-1 (Fig. 4). Above an altitude of 850–900 meters asl there would be an improvement in site conditions and a resulting increase in annual biomass increment reaching about 2 Mg·ha-1 in the highest positions in the mountains, which would result primarily from the more beneficial thermal conditions in this zone – currently the limiting factor for the growth and vegetation of Norway spruce. Using model 8, based on the MAT and MAP values mapped out according to the two projected scenarios for each pixel of the DTM, the potential values for the current annual biomass increment were calculated, which enabled the mapping of the projected potential site productivity. The difference between the current and future potential productivity was used to map changes in the site productivity for the projected level of carbon dioxide concentration (Fig. 5, 6). Doubling the concentration of carbon dioxide would cause almost the entire study area, with the exception of the highest mountain altitudes, to deteriorate in terms of spruce vegetation. The consequence would be to reduce the biomass increment, particularly evident in the lowest positions in the target zone from 300 to 800 metres asl (Fig. 5).

For the second scenario adopted, the reduction of growth would occur in a slightly smaller area, and its scale would be much smaller. A relatively large area encompassing parts of the main peaks of the mountain ranges there would be an increase in biomass increment (Fig. 6).

Discussion

Analysis of the projected temperature conditions in the Western Beskids indicates that the annual mean temperature will rise compared to data from the years 1957–1986. This increase is most noticeable for the summertime mean. The indicators based on the GISS_E scenario are extremely negative. They assume a further upward trend of 0.32°C within 10 years. The consequence of this would be to extend the growing season in extreme cases by up to 1 month (Tab. 1). Analysis of projected pluvial conditions in the Silesian Beskids points to maintaining the current level of total annual precipitation in relation to archival data from the years 1957–1980. Several years less abundant in rainfall around the turn of the century (1981–2008) resulted in slightly lower long-term total. However, indicators for both 2009 and 2010 compensate for this degradation in the context of the last decade. Rainfall indicators are worse for summer and the growing season. It is now down 8% compared to data from the 1960s and 70s. The projection is made based on the GISS scenarios in the first case gives a figure of 12% and the second by nearly 9% lower. These results are not optimistic, if we take into account the requirements of spruce in this climatic zone. In the lowest areas, the warmer, less humid conditions on the southern and south-western slopes have previously been described as limiting factors for the growth of spruce in the lower parts of the mountains in the Carpathians (Gieruszyński 1936; Socha 2008, 2010). It therefore seems indisputable that the projected

increase in temperature and decrease in precipitation in the summer will contribute to the deterioration of conditions for growth and its associated increment in spruce stands in the lower parts of the Western Beskids.

The average annual air temperature in the Silesian Beskids over the past 50 years has shown a positive directional change (0.71°C), but the evaluation of this model was not statistically significant. Assuming, in spite of all, that the coefficient of the regression function would maintain a similar level until 2050, it is expected that the average annual air temperature in the Western Beskids would be 7.2°C with a deviation of 0.9°C. Similar conclusions are presented by Migała in his paper (2005) indicating analogous parameters for his arbitrarily adopted "minimum hypothesis" for selected stations in the Western Carpathians. Analysing the data series on the concentration of CO_2 from the region of the Central Europe and Western Carpathians, it is difficult to accept the forecasts contained in the first three IPCC reports of 1990, 1995 and 2001 (Smith and Pitts 1997). The authors of subsequent studies, however, have reduced the initial assumptions, an example of which is the image, far deviated from previous ones, of the future climate in Europe included in the IPCC's last report (Bernstein at al. 2007). The variant proposed in the fourth IPCC synthesis averaged from 6 climate models gives a range from 1.1°C to 2.8°C in 2050. Thus, the results obtained for the variant in which the CO_2 concentration increases by 30% is close to the lower limit of the optimistic scenario (Solomon et al. 2007). The model adopted for the purpose of this study gave similar projected values, because the change in average annual air temperature in the Silesian and Żywiec Beskids to the year 2100 was estimated at 1.1°C with a deviation of 0.8°C. The above situation should not, therefore, result in visible changes in plant ecosystems in the region over the coming decades. The situation presents itself differently if, in the modelling, we consider the forecast parameters proposed in the third IPCC report (McCarthy et al. 2001). The resulting indicators show fairly radical changes in the climate regime of the area. The increase in mean summer temperature or growing season temperature in the range provided for the GISS_E ($2 \times CO_2$) scenario may significantly disrupt the existing phytoclimatic system. The projected change may cause expansion of phenomena observed thus far only in the foothills, and a gradual shift in climate boundaries of even more than 250 meters. On the basis of the analysis, it may be assumed that these conditions may be unsuitable for spruce vegetation to an elevation of about 800 metres asl. This situation may significantly reduce the adaptation capability of spruce stands, not only because of the projected pace of change, but also because of the biology of this species (Socha 2010a, 2010b; Durło 2011).

In terms of pluvial climate, differences show up especially in terms of precipitation totals on a quarterly basis. Indicators of the current climate differ noticeably from the historical data. Above all, there is a discernible reduction in total summer rainfall in favour of precipitation during winter (Tab. 2). In a variant similar to the current situation, the index showing the ratio of winter to summer rainfall remains unchanged at around 70%, in the case of winter rainfall increase by 15% in 2050 (GISS_E), it is expected that this ratio will increase to a level of 83%. In the situation where the growing season would last on average 225 days a year and rainfall distribution would be uniform, this would not satisfy even 80% of the needs of lower subalpine stands. In our opinion, however, such a trend seems unlikely. Given the results of the analysis and the results of modelling the likely changes in the future, it seems that the scenario assuming increases in the average annual air temperature of 1.0°C and increased precipitation during the winter of 5% with a slight reduction in total precipitation in July and August is the more realistic.

Because of the nature of the described dependencies estimated in the projection, the changes in habitat conditions for spruce expressed by changing the potential productivity increment are characterised by some degree of uncertainty, due to several reasons:

– In modelling site productivity two basic climatic factors, such as annual precipitation and annual average temperature were used, which in the Western Beskid Mountains play a key role in the growth of Norway spruce. The growth of spruce stands also depends on other factors, which include fertility and soil moisture associated with the soil parent rock (Sikorska 2004; Socha 2008). Soil-forming processes, which determine the type of soil, are affected by geological substratum, climate and site topography. Changing climatic conditions would consequently also change soil properties. Therefore, the projected incremental effect due to increased air temperature,

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Tab. 2. The temperature and rainfall indexes (°C, mm, days) for different periods and prognoses of GISS_E (2 × CO_2) and GISS_E_WC (1.3 × CO_2) scenarios

Indexes	Period 1957–1986	Period 1987–2006	GISS_E	GISS_E_WC
Mean annual air temperature	5,5	6,2	8,9	6,9
Mean spring air temperature	5,1	5,8	9,0	6,7
Mean summer air temperature	13,6	14,2	17,1	15,3
Mean autumn air temperature	4,0	3,9	6,6	4,8
Mean winter air temperature	–3,3	–3,2	–0,2	–2,3
Average sum of annual precipitation	1306	1279	1303	1308
Average sum of spring precipitation	365	356	345	345
Average sum of summer precipitation	419	368	357	381
Average sum of autumn precipitation	268	290	304	308
Average sum of winter precipitation	252	264	297	274
Average ratio of winter to summer sum of precipitation (%)	61,0	72,0	83,0	72,0

due to the long-term nature of soil-forming processes on the backdrop of a century-long projection, may be somewhat weaker.

– Another of the factors which, due to the complexity of the analysed dependencies, may increase the uncertainty of estimates of incremental responses is change in the concentration of CO_2 and NO_x in the atmosphere. Most authors agree that the increased concentration of carbon dioxide will increase the growth of forest stands (Zheng et al. 2002; Albert and Schmidt 2010). In the studies presented, the effect of increased CO_2 concentrations were analysed only in the context of raising the average temperature; the additional physiological effect associated with the larger availability of CO_2 for plants and the efficiency of photosynthesis was not analysed.
– An important yet difficult to capture factor that may be of crucial importance for the course of growth spruce stands in the forecast period are extreme weather events, especially droughts, extreme precipitations and wind events, which in recent years have significantly influenced the health of spruce stands in the Western Beskids. It seems that prolonged droughts during the summer, which occurred in 1993, 2003, 2006 and 2008, were one of the main reasons for the reduction in the stability of spruce stands and their decay over a wide area of the test region. Analysis of the sequence of events leading to the disintegration of spruce stands in the lower montane zone allows the hypothesis that the growth in mean annual air temperature observed in the last two decades has already had a negative impact on the health of trees and growth of stands. In both variants, the results presented indicate a reduction in biomass increment of stands in the lower montane zone. To reduce the risks associated with increasingly frequent extreme weather events, we should aim to shape less dense stands, with trees with better developed and longer crowns, and simultaneously much better developed root systems. Such stands are less desirable from an economic point of view; however, they are much more resistant to the stress associated with the adverse effects of abiotic factors (Zajączkowski 1991).

Conclusions

The observed trend of increasing mean annual air temperature causes the modification of the vertical range of climate belts and related changes in habitat conditions. In the case of scenario assuming the doubling of CO_2 concentration in the atmosphere, the cool floor will most likely decay and the moderately cool floor will partially disappear in the Western Beskid Mountains, and the borders of climate floors may move up to 250 m. The growth in mean annual temperature projected under this scenario of about 2.7°C

and the reduction in the rainfall during the growing season by about 70 mm would result in a significant deterioration in conditions for spruce growth. In the new, altered habitat conditions, spruce could still play a role as an afforestation species only in the highest locations asl over 1000 m. This would create a need to change the species composition of stands in most parts of the forested area in this region.

A slightly better prospect for the growth of spruce in the Western Beskid Mountains would take place in the GISS_E_WC scenario, which assumes a 30% increase in CO_2 concentrations. As a result of the increase in mean annual air temperature by about 0.7ºC while maintaining the current level of mean annual precipitation and a slight reduction in rainfall during the growing season, a slight deterioration in habitat conditions to a height of about 800 m asl, optimal growth conditions for spruce would occur only in the zone between 850 and 1000 m asl.

These analyses of spruce habitat conditions in the Western Beskids may be the basis for decisions concerning the future role of this species in the species composition of stands, depending on their location. The main goal of the study was to conduct projections for changes in spruce habitat conditions in hypothetical climatic scenarios. The likelihood that these scenarios come to pass and long term (decades) maintenance of presently observed trends in climate change consisting mainly of growth in atmospheric concentrations of CO_2 and an increase in the mean annual temperature is a separate issue. However, regardless of whether the adopted scenarios become real, an increase in temperature and a decrease in total precipitation in the growing season, resulting in deterioration of spruce growing conditions, has already been observed. The scale of this phenomenon for various habitat conditions can be predicted using the models developed. The results indicate that even a slight increase in mean annual temperature may adversely affect the growth and development of spruce stands over a large area of the Beskids.

Despite uncertainty about the scale of projected climate change, the likely trends in the development of habitat conditions for the growth of spruce in the Western Beskid Mountains can be determined. Regardless of the degree of global warming, the decline of spruce forest stands in Central Europe's mountains already observed is likely to intensify, especially in the lower altitudes. The slight projected improvement in terms of growth in the higher altitudes related to the improvement of thermal conditions is contingent upon the absence of periods of drought and other extreme weather events whose occurrence may reduce the stimulatory effect of elevated temperature on the forest stands. The projected scale of change in habitat conditions is burdened by uncertainty associated with a number of factors; less uncertainty, however, shrouds the directional changes of the indices analysed. Therefore, to ensure the sustainability of forest ecosystems in mountain areas of Central Europe, economic activity should be carried out to spread the risk, which would enable the forest ecosystems to be prepared for different climate change scenarios. Activities of this type should include conversion of the pure spruce stands preferred in the mountains of Central Europe over the last century into mixed stands. These actions should be implemented particularly in the lower and middle altitudes of the mountains, and the stands should have a significant share of deciduous species such as: beech and fir, sycamore, elm, and ash.

Given the growing importance of numerous non-production functions of mountain forests, the primary objective of management in these areas should be to ensure the sustainability of forest ecosystems and to prepare them for possible future threats. In this period of such observed phenomena, the economic role of forests in these areas now passes into the background.

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